

Mt. Everest Biogas Digester Basis of Design

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Preliminary Schematic Design

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Introduction

Mt. Everest, known in Nepali as Sagarmatha, serves as the ultimate challenge and lifelong goal for hundreds of climbers every year. It is the world's highest mountain, but more importantly it is sacred to the local Sherpa communities who refer to the mountain as the Mother Goddess of the World. Climbers are welcomed as they benefit the local economy by spending money at the teahouses in the Khumbu valley and provide employment to porters and climbing Sherpas. However the mountain's increasing popularity is causing a tremendous environmental impact to the pristine and fragile environment of Sagarmatha National Park.

Every year, 13.23 tons (26,460 lb or 12,000 kg) of human waste solids from the base camps of Mt. Everest, Pumori, Lhotse and Nupste are carried in blue barrels by porters and dumped into open unlined pits at Gorak Shep, elevation 16,942 ft (5,164m) (*based on Sagarmatha Pollution Control Committee's Annual Progress Report published in 2011*). This disposal of the climbers' human waste is an environmental hazard, as it is potentially contaminating the water supply at and below Gorak Shep and is considered disrespectful to Sagarmatha by the Sherpa community.



Figure 1



Figure 2 The Khumbu valley trail

Since 1991 Sagarmatha Pollution Control Committee (SPCC), a Non-Government Organization made up of the local people of the Khumbu valley has led the effort to clean up the national park, from Everest Base Camp (EBC) down through the Khumbu valley. Their work has been very successful, though mostly focusing on garbage removal. SPCC has also taken the responsibility to organize the removal of human waste from the EBC. Unfortunately, due to the rugged and remote nature of this area, disposal into unlined pits has been the only practical response to the massive human waste problem there. In March 2014, the Nepalese government announced new regulations to protect the environment of Sagarmatha by requiring climbers to haul garbage, including human waste, from camps above EBC. This mandate does not address what to do with the additional human waste, which leaves the current practice of open pits to deal with it.

This project proposes to use an anaerobic biogas digester to treat the human waste brought down from EBC. This biogas digester, built with the help of Biogas Sector Partnership Nepal (BSP), will be able to destroy pathogenic fecal coliforms while also generating biogas for the local

Sherpa community. The biogas produced by anaerobic digestion is a mixture of CO₂ and methane that burns readily, it can easily be used as a fuel for cooking or heating.

The site for this project cannot be Everest Basecamp, as this camp is located on the Khumbu Glacier and can only be occupied transiently. This leaves Gorak Shep as the nearest possible site for treating the human waste. Figure 4 below shows the proposed biogas digester site and its relationship to the porters' shelter and teahouses of Gorak Shep. The kitchen of the porters' shelter is about 200 ft (~60m) from the proposed site, making it possible to pipe the biogas directly to their stove.

It must also be mentioned that this proposed location for the project is within the Sagarmatha National Park, which will require permission from and collaboration with: the National Park and Wildlife Conservation Office, Department of National Parks and Wildlife Conservation, Ministry of Forests., Government of Nepal and the local Buffer Zone Committee (<http://whc.unesco.org/en/list/120>).



Figure 3



Figure 4

Please see **Appendix A** for interviews with local stakeholders stating their reaction to the dumping of human waste and the proposed biogas solution in their own (translated) words.

Design Conditions

The microorganisms that produce biogas in BSP digesters require an internal temperature of 68°F-86°F (20-30°C). No biogas digester has ever been built in an environment as extreme as Gorak Shep, since heat loss from a warm biogas digester into the cold soil surrounding it is unavoidable. Balancing this heat loss, to maintain the digester required temperature, is thus the major obstacle to the success of this project. To replace the lost heat, there must be a sustainable and readily available form of energy for year-round operation. In the remote location of Gorak Shep, solar energy is the only plausible solution.

This creates two limiting cases to achieving the necessary digester temperatures. The first is the extremely cold temperatures of the winter months, when the ambient conditions are much colder than the required digester temperatures. The other limiting case is the summer monsoon season, when the available solar energy is greatly decreased due to intense cloud cover.

Additionally, any heating solution must meet the requirements for Gorak Shep of being off the shelf, low technology, available in Nepal, and very rugged to endure the 5-6 day transportation to

Gorak Shep. Only products that were successful in similar applications will be used. The entire design must be achievable with local construction techniques, including skilled and unskilled local labor, and transportation to the site by human porters or with pack animals.

Heat loss from the digester is *the* major issue for this project, but there is also a need to heat the slurry that goes into it. To keep the digester's internal temperature stable, the batch of slurry that is added each day must be heated to ~86°F (~30°C), which will require a considerable amount of energy. BSP digesters require year round operation with a new batch of slurry added each day. This slurry is made by mixing the human waste with water in a 1:1 ratio. But since the human waste at Gorak Shep arrives mostly during the spring climbing season and partially in the fall climbing season; the system must be able to store water and some of the waste from one spring climbing season to the next. To limit the amount of energy needed to heat the slurry, the water and human waste in storage must never be allowed to freeze.

Considering these issues with slurry storage and heating, as well as the digester's required temperature and related heat loss, it is easy to see why no one has attempted biogas digestion in an environment like Gorak Shep before.

Digester Sizing and Logistics

The sizing and operation for this project's biogas digester are based on BSP's *Design Choice Parameters of Medium Sized Biogas Plants* (Which can be found in **Appendix B**). The governing parameters for these plug flow reactor biogas plants are quite straightforward.

- The recommended slurry ratio is: one volume water to one volume waste. Due to lack of data our team has assumed both waste & water to have a density ~8.34 lb_f/gal (~1Kg/L)

Slurry dilution ratio is 1:1

- For biogas plants digesting only night soil (human waste) a hydraulic retention time of 70-90 days is recommended to ensure pathogen destruction.

T_{hr} 70-90 days for night soil

- Digester sizing and feed rate are related to retention time by the simple equation:

$$\text{Hydraulic Retention Time } (\tau_{hr}) = \text{Digester Volume} / \text{Feed Rate}$$

- Biogas production is given as:

0.020-0.028 m³ biogas/Kg night soil (2.396 gal biogas/lb_m night soil)

To keep the work brief and clear, the convention for citing units used in the majority of this document: USCS (SI), is not used in the rest of this section. This was done because both the information given by SPCC and BSP are in SI units. However certain key pieces will also be shown in USCS.

To determine the size of digester needed, first the feed rate was calculated as:

$$\begin{aligned} \text{Daily Feed Rate} &= \text{Annual Waste} / 365 \text{ days} = 12\,000 \text{ Kg night soil} / 365 \text{ days} \\ \text{Daily Fee Rate} &= \mathbf{32.9 \text{ Kg night soil/day}} \end{aligned}$$

As both water and night soil were assumed to have a density ~1Kg/L the volume of slurry at 1:1 volumetric dilution would be:

$$\begin{aligned} \text{Slurry Feed Rate} &= 2 * 32.9 \text{ L night soil/day} \\ \text{Slurry Feed Rate} &= 65.8 \text{ L} \frac{\text{slurry}}{\text{day}} \quad (17.37 \text{ gal slurry/day}) \\ \text{That is: } &32.9 \text{ L waste/day} \quad (8.69 \text{ gal waste/day}) \\ \text{And: } &32.9 \text{ L water/day} \quad (8.69 \text{ gal water/day}) \end{aligned}$$

The larger recommended τ_{hr} of 90 days was chosen, so that more waste could be processed later if necessary, by decreasing τ_{hr} to 70 days. To size the digester then, the governing equation for the digester was rearranged:

$$\begin{aligned} \text{Digester Volume} &= \tau_{hr} * \text{Slurry Feed Rate} = 90 \text{ days} * 65.8 \text{ L} \frac{\text{Slurry}}{\text{day}} \\ \text{Digester Volume} &= 5\,922 \text{ L} \quad (5.922 \text{ m}^3) \end{aligned}$$

BSP digesters are built in either: 4 m³, 6 m³ or 8 m³ sizes. Naturally the 6 m³ model was the closest choice. The shape and dimensions of such a 6 m³ BSP digester are described below in Figure 5.

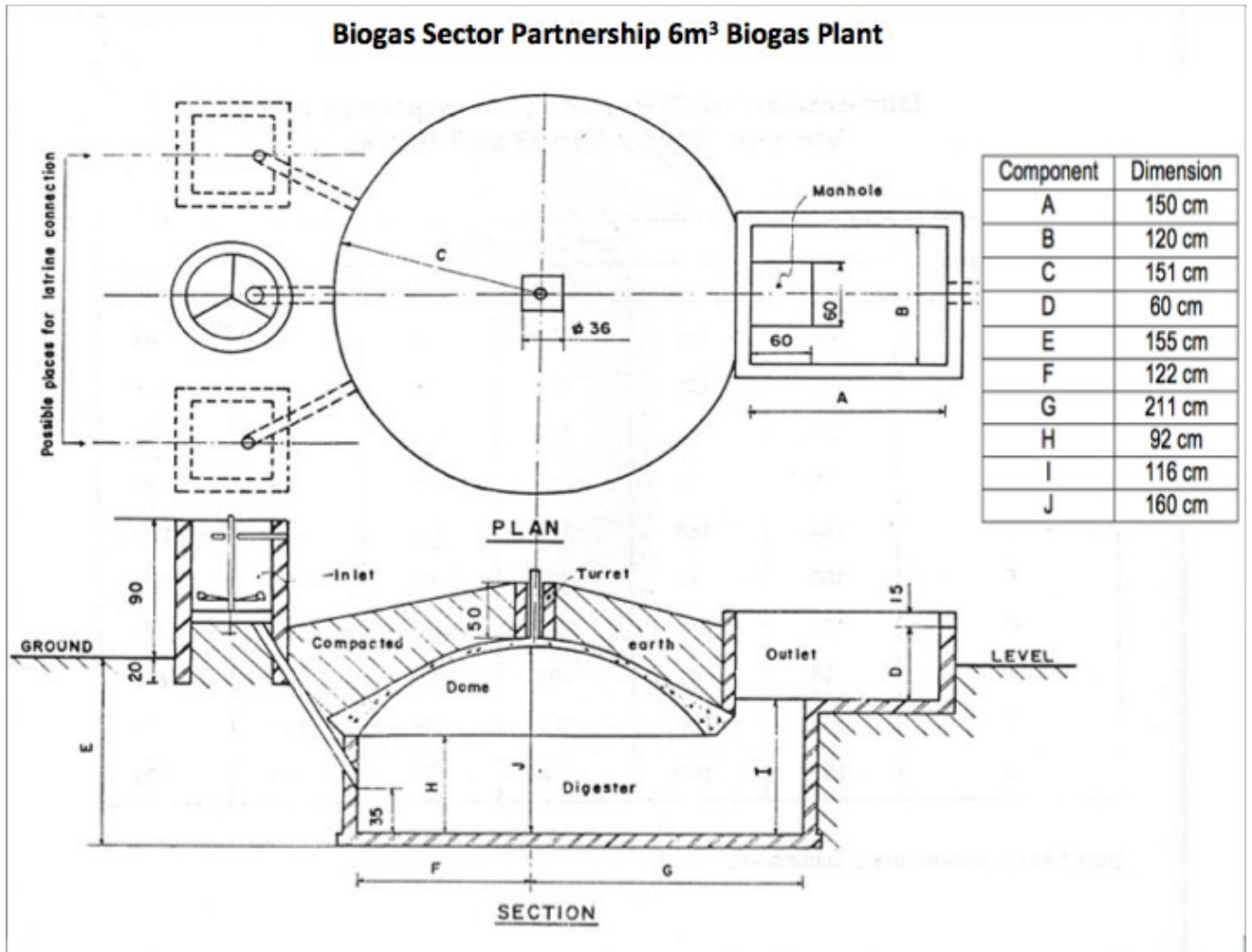


Figure 5

With a 90 day τ_{hr} and a 6 m³ digester, there will be a slight shortfall in waste needed for the digester during a year of operation. This difference was found by rearranging BSP fundamental equation once more:

$$\begin{aligned} \text{Daily Feed Rate} &= \text{Digester Volume} / \tau_{hr} = 6 \text{ m}^3 / 90 \text{ days} = 6\,000 \text{ L} / 90 \text{ days} \\ \text{Daily Feed Rate} &= 66.67 \text{ L/day} \quad (17.6 \text{ gal slurry/day}) \end{aligned}$$

Comparing the differences between slurry feed rates shows the short fall:

$$(66.67 \text{ L / day}) - \left(65.8 \frac{\text{L}}{\text{day}} \right) = 0.87 \frac{\text{L}}{\text{day}} \text{ or } 0.87 \frac{\text{Kg}}{\text{day}} \quad 1.9 \text{ lb}_m / \text{day}$$

Since only half of this slurry is actually waste, this means that only 0.435 Kg (0.959 lb_m) of waste would be additionally required daily. This shortfall can easily be made up with kitchen scraps during the tourist season, or even caretakers' waste during the winter.

It should also be mentioned that Professor Bed Mani at Kathmandu University has successfully produced biogas in bench-scale experiments using only climbers' waste from Mt Everest Base Camp. These experiments were conducted at a range of temperatures, including 68°F and 86°F (20 and 30°C). The successful production of biogas at these temperatures from climbers' waste has satisfied the concern that biogas formation could be suppressed by antibiotics in climbers' waste. Although this does not prove that a full-scale biogas plant will not have issues due to antibiotic toxicity, it does give a proof of concept. It is possible to make biogas, using only Everest Base-Camp climbers' waste as a substrate.

Ground Temperature Data and Modeling

Figure 6 below shows a graph of temperature 7.9 in (~0.65 ft or 20 cm) below the ground's surface in Luboche, half a days walk below Gorak Shep. This data was collected by the Italian research station EVK2 in Luboche from 2003 to 2010. The graph shows the worst temperatures, sometimes below 23°F (-5°C), to occur in the winter, between January and March. While the summer months see temperatures sometimes higher than 50°F (10°C). This data was the best information available for understanding Gorak Shep's soil temperature, but unfortunately it only describes a very shallow depth into the soil. To guide the project's design, the temperatures at the digester's bottom 5 ft (1.55m) below the surface were needed. Specifically, the ground temperature at the digester's bottom needed to be understood during the project's two limiting cases (maximum cold temperature in winter and minimum solar energy in summer).

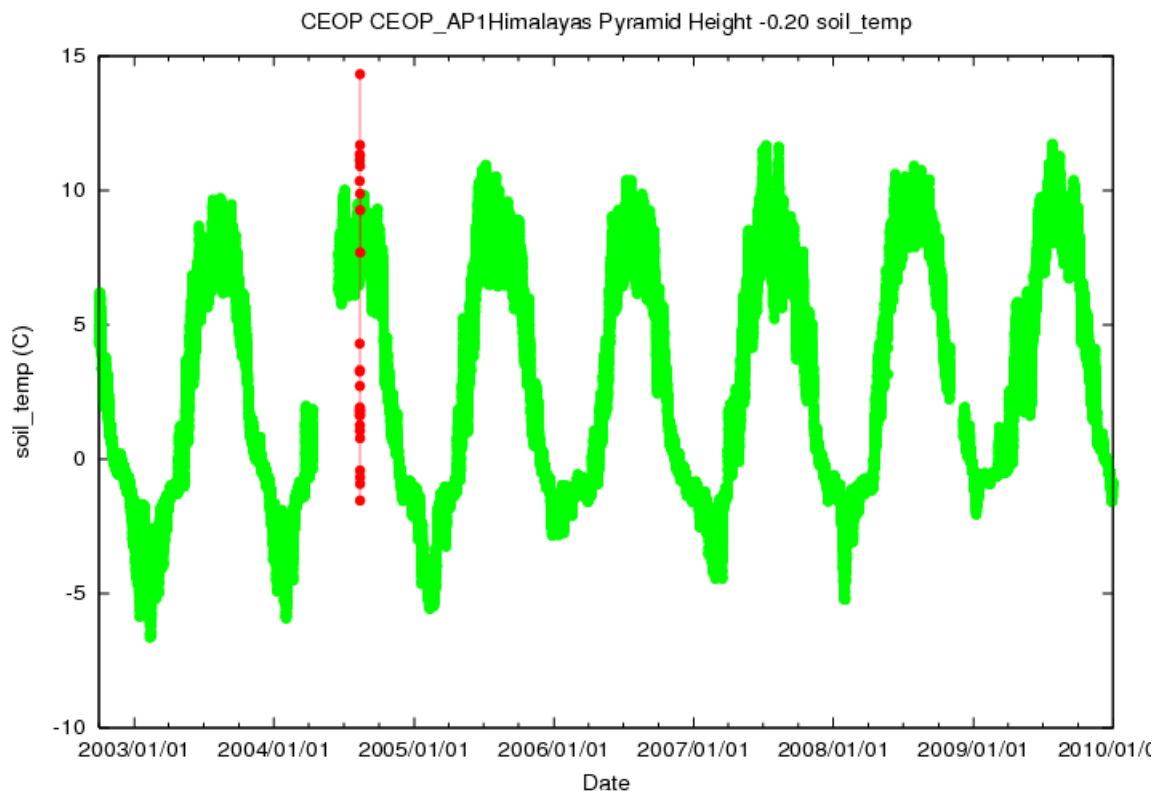


Figure 6

To better understand soil temperature at different depths, the Kasuda Equation, a correlation between the ambient air temperature and soil depth was used:

$$T = T_{mean} - T_{amp} \times \exp \left[-Depth \times \sqrt{\frac{\pi}{365 \times \alpha}} \right] \times \cos \left\{ \frac{2\pi}{365} \left[t_{now} - t_{shift} - \frac{Depth}{2} \times \sqrt{\frac{365}{\pi \times \alpha}} \right] \right\}$$

The Kasuda equation suggests that the temperature of the ground is a function of time of year and depth below the surface. Average ambient air temperature, thermal diffusivity of the soil and amplitude of the surface temperature are the main variables of the equation. The values used in the equation for T_{mean} , T_{max} and T_{min} were taken from a TMY2 data set for Gorak Shep. TMY2 stands for Typical Meteorological Year (2nd iteration), these are based on data sets derived from 1961-1990, collected by the National Solar Radiation Data Base. TMY2 data list hourly values of solar radiation and meteorological elements for a 1-year period (<http://rredc.nrel.gov/solar/pubs/tmy2/preface.html>).

The TMY2 data set for Gorak Shep was generously donated to the Mt Everest Biogas Project by Weather Analytics. During the project's site survey in June 2013, the soil type of the proposed digester site was determined to be dry sand. Thus the thermal diffusivity of dry sand was used for the alpha value in the equation (Farouki, O. T. 1981. Thermal Properties of Soils. U.S. Army CRREL Monograph 81-1.136 pg. 12). Using all this information, Tables 1, 2, 3 and Figures 7, 8 below were generated. The table values at the depth of 0.65 ft (0.20 m) are shown in orange; these are highlighted for comparison with the values in Figure 6. The Table values shown in red represent the minimum and maximum temperatures modeled for the bottom of the digester.

Table 1

T_{mean}	36.91 °F	2.73 °C	Mean surface temperature (average air temperature)
T_{amp}	40.23 °F	22.35 °C	Amplitude of surface temperature [(maximum air temperature - minimum air temperature)/2]
T_{max}	64.94 °F	18.3 °C	Maximum air temperature
T_{min}	-15.52 °F	-26.4 °C	Minimum air temperature
α	0.093 ft ² /d	0.0086 m ² /d	Thermal diffusivity of the ground for dry sand
t_{now}			Days of the year to get a year long profile
t_{shift}	2 Days		Day of the year of the minimum surface temperature

Table 2

Depth	Days 0	50	100	150	200	250	300	350	365
0 ft	-3.30 °F	9.64 °F	41.54 °F	70.22 °F	75.73 °F	54.24 °F	20.70 °F	-1.57 °F	-3.29 °F
0.65 ft	4.78 °F	10.20 °F	34.19 °F	60.08 °F	69.85 °F	56.71 °F	29.80 °F	7.83 °F	4.81 °F
1 ft	8.91 °F	11.18 °F	31.34 °F	55.38 °F	66.57 °F	57.13 °F	33.63 °F	12.41 °F	8.95 °F
2 ft	19.38 °F	15.53 °F	26.55 °F	44.77 °F	57.53 °F	55.94 °F	41.12 °F	23.37 °F	19.42 °F
4 ft	33.16 °F	25.89 °F	26.28 °F	34.07 °F	43.83 °F	48.78 °F	45.47 °F	36.21 °F	33.20 °F
5 ft	36.77 °F	30.16 °F	28.24 °F	32.35 °F	39.64 °F	45.02 °F	44.77 °F	39.05 °F	36.80 °F
6.56 ft	39.33 °F	34.77 °F	31.70 °F	32.25 °F	36.04 °F	40.44 °F	42.38 °F	40.52 °F	39.35 °F
10 ft	38.83 °F	38.06 °F	36.50 °F	35.22 °F	35.12 °F	36.26 °F	37.86 °F	38.80 °F	38.83 °F
65 ft	36.91 °F	36.91 °F	36.91 °F	36.91 °F	36.91 °F	36.91 °F	36.91 °F	36.91 °F	36.91 °F

Table 3

Depth	Days 0	50	100	150	200	250	300	350	365
0 m	-19.61 °C	-12.42 °C	5.30 °C	21.24	24.30 °C	12.36 °C	-6.28 °C	-18.65 °C	-19.60 °C
0.2 m	-15.08 °C	-12.10 °C	1.19 °C	15.55	21.00 °C	13.74 °C	-1.18 °C	-13.38 °C	-15.06 °C
0.5 m	-8.96 °C	-10.12 °C	-2.35 °C	8.96	15.93 °C	13.72 °C	3.87 °C	-6.78 °C	-8.93 °C
1 m	-1.50 °C	-5.39 °C	-3.63 °C	2.55	8.86 °C	10.90 °C	7.27 °C	0.47 °C	-1.47 °C
1.5 m	2.53 °C	-1.19 °C	-2.18 °C	0.24	4.39 °C	7.39 °C	7.15 °C	3.83 °C	2.55 °C
1.55 m	2.78 °C	-0.85 °C	-1.98 °C	0.16	4.09 °C	7.07 °C	7.04 °C	4.01 °C	2.79 °C
2 m	4.08 °C	1.54 °C	-0.16 °C	0.14	2.25 °C	4.69 °C	5.77 °C	4.73 °C	4.09 °C
2.5 m	4.24 °C	2.91 °C	1.46 °C	0.89	1.60 °C	3.10 °C	4.34 °C	4.46 °C	4.24 °C
20 m	2.73 °C	2.73 °C	2.73 °C	2.73	2.73 °C	2.73 °C	2.73 °C	2.73 °C	2.73 °C

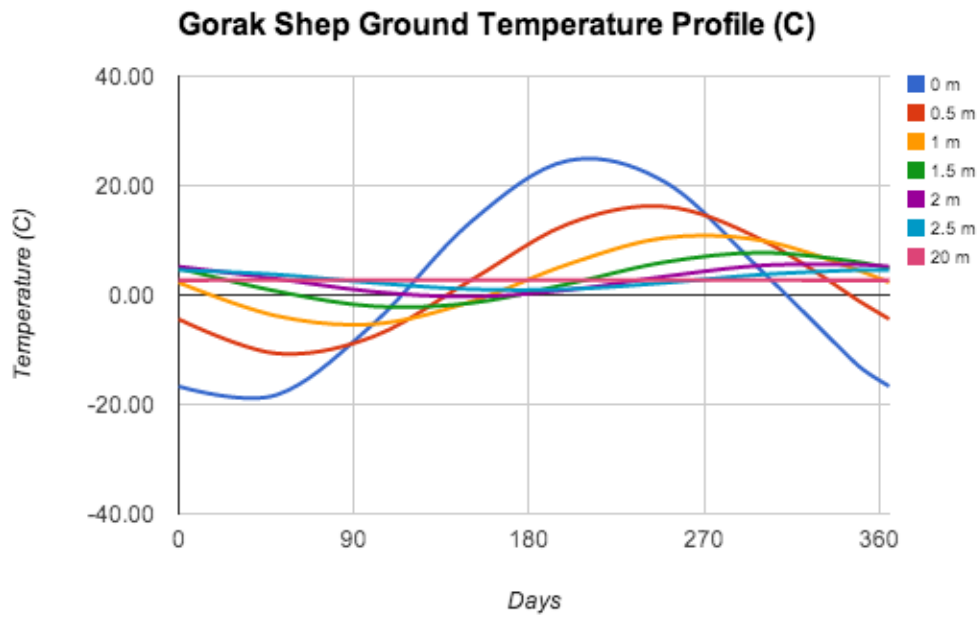


Figure 7

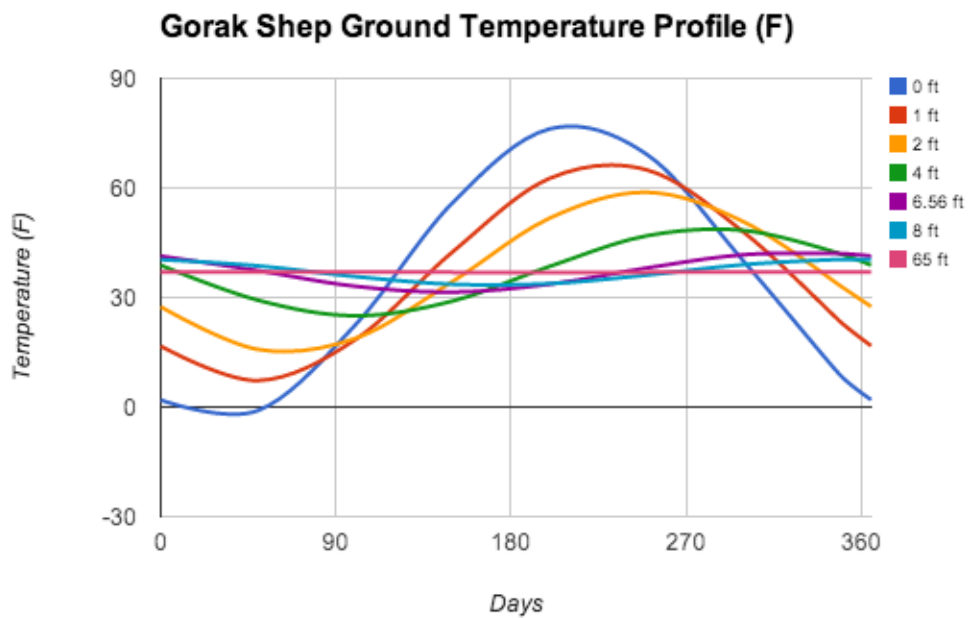


Figure 8

Comparison of the Luboche data (in Figure 6), with the values modeled at the same depth with the Kasuda equation, shows they are not the same. The Kasuda equation captures the qualitative rise and fall of the soil temperature well, but quantitatively the values do not match. The modeled minimum temperatures are about 50°F (10°C) lower than the Luboche data and the modeled maximum temperature is about 50°F (10°C) higher than the Luboche data. This variance may be due to the soil type at Luboche differing from that of the sandy project site at Gorak Shep (The Italian's research paper reports the soil to be 39.42% Sand, 58.19% Silt and 2.39% Clay. See **Appendix C** for this report).

The discrepancy between the Luboche data and the Kasuda equation's values show that the modeled values should not be used for design work. But since the modeled values display a greater variance than the data, the modeled values can be used to guide conservative estimates for the ground temperature at the digester's bottom.

Qualitatively, the Kasuda equation describes ground temperature varying less as the soil depth increases. This led the design team to choose -5°C for the winter's minimum temperature. This temperature was chosen since it was the minimum value reported in the Luboche data at 0.20m, and thus it is unlikely to occur at the depth of the digester's bottom. Following this same train of logic, values ~3°C less than the modeled values were chosen to arrive at a conservative design temperature for summer. In Table 2 the minimum temperature 5 ft (1.55 m) below the surface is 28.24°F (-1.98°C) and the maximum temperature is 45.02°F (7.07°C). From these values, the design temperature for winter was chosen to be 23°F (-5°C) and the design temperature for summer was chosen to be 39.2°F (4°C).

It should also be noted that both the Luboche data and the Kasuda equation only deal with naked soil. They both describe changes in soil temperature that are solely due to changes in ambient conditions. This makes the use of the data and modeling described above especially conservative for design work, as the soil in contact with the digester will not be subject to ambient conditions. The final system will involve a shelter above the digester, regulating its interactions with the ambient weather. Also the heat loss of the digester into the sandy soil will serve to raise the temperature of the nearby soil.

Heat Loss Model

The dimensions given for a ~6 yd³ (6m³) Biogas Plant listed in BSP's Construction Manual (http://journeytoforever.org/biofuel_library/methane_nepal.html) were used to determine the surface areas of the biogas digester's various components. A simplifying assumption was made, that the slurry in the digester and the gas collecting in the dome could be treated as one constant internal temperature for the digester.

The heat conduction, from this internal temperature, through the surface area of the digester's components was calculated using the standard Heat Conduction Rate equation:

$$q = (k * A * \Delta T)/t$$

k is a material's thermal conductivity, A is its surface area, ΔT is the temperature difference between the digester's internal temp and the surrounding ground and t is the material thickness.

This equation was rearranged to use Thermal Resistance or R-Values, where $R = t/k$

$$q = (A * \Delta T)/R$$

This conductive heat loss was calculated for each digester component, and these losses summed to determine the overall conductive heat loss of the digester.

The R-value for cement was used in the case of all the walls and the dome of the digester. The lid on the digester's outlet was considered to have the R-value of wood. As this design aims to add insulation on all these surfaces equal to R-50 (USCS not SI), this additional thermal resistance was added to the R-values of the walls, dome and lid.

Using the assumptions shown in Table 3 below and the model described above, the heat loss for a $\sim 6\text{ y}^3$ (6 m^3) digester was calculated to be 351.54 BTU/hr (103 W) in the winter case and 262.80 BTU/hr (77 W) in the summer case.

Table 4

Desired internal temperature	68°F	30°C
Ground temperature surrounding the digester in winter	23°F	-5°C
Ground temperature surrounding the digester in summer	39°F	4°C
Assumed Air Temperature surrounding the digester	32°F	0°C
Slurry temperature when added to digester	68°F	30°C
Insulation of the complete digester	R-50 USCS	R-8.81 SI

The Heat Loss Model is an Excel spreadsheet in **Appendix D**.

General Description of Enclosure Design

There are over 200,000 BSP digesters functioning in Nepal, making them the obvious choice for this project. As mention above, the biogas digester that can process 13.23 tons (26,460 lb or 12,000 kg) of waste in a year must have an $\sim 6\text{ yd}^3$ (6 m^3) volume. For the purposes of this project, the BSP digester is considered to be an off-the-shelf design. The design proposed for this

project will only make external modifications to allow BSP's digester design to function in the cold environment of Gorak Shep. Without such considerations, the 351.54 BTU/hr (103W) heat loss described in the preceding section will drop the digester's internal temperature below the operating range of 68°F-86°F (20-30°C). Below this range the microorganisms in the slurry will not be able to effectively destroy fecal coliforms or produce biogas.

The design to ensure the digester stays in its operating range has four main elements added to the BSP digester. The design elements are:

1) Building and storage for Water & Climbers' Waste

A) Shelter building to keep the digester, stored water and battery bank above 32°F (0°C)

B) Water storage (inside the shelter)

C) Waste storage keeping waste cool but not frozen (outside the shelter)

2) Heating the biogas digester to maintain 68°F-86°F (20-30°C)

3) Heating of the water & waste to make ~86°F (~30°C) slurry to feed the digester daily

4) Electrical power for Elements 2 & 3 using:

A) PV solar panels

B) Batteries in series

Element 1

A)

To store the water for slurry above freezing, a well-insulated masonry building will protect the digester, the battery bank, stored water. This building will follow local architecture, being made of locally quarried and shaped granite masonry. The current design is shown in the following Figures 9-12 below. All building materials used will be proven by previous use in the Khumbu valley and available in Kathmandu or Namche Bazaar. The South wall of the building will be angled to allow more solar heating and contain three windows. These windows will be hand constructed, with multiple smaller window modules in each window frame. All window modules will have two panes of glazing material to limit heat loss out of the windows. Behind these windows the rainwater will be stored inside five 3,000 Liter tanks. These water tanks are explained as part of section **B** below.

Digested slurry will flow by gravity out of the building through a drain pipe to a drain field where the digested slurry will be disposed below the soil surface. The drain pipe from the digester's outlet will drop 7 ft (~2.1 m) before leading to perforated pipes distributing the treated liquid into the sandy soil. This depth has been chosen to avoid freezing issues in the perforated pipes (refer to **Ground Temperature Data and Modeling section**).

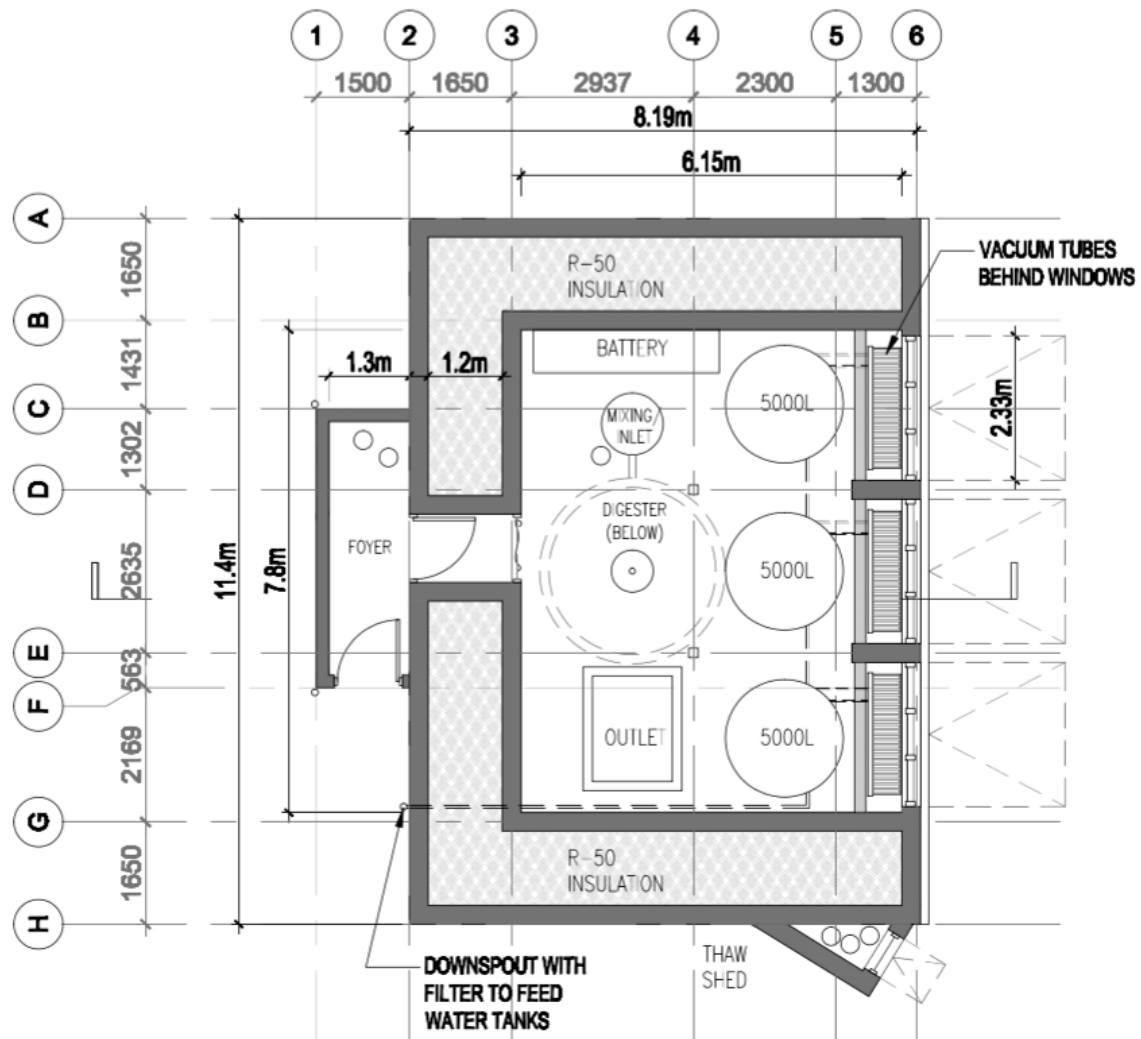


Figure 9

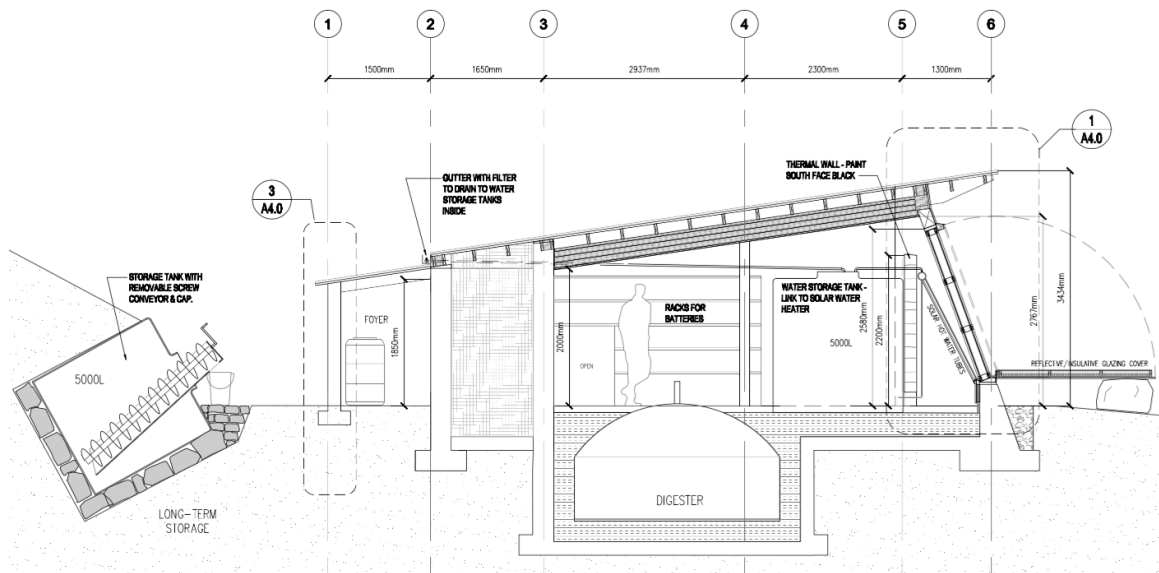


Figure 10

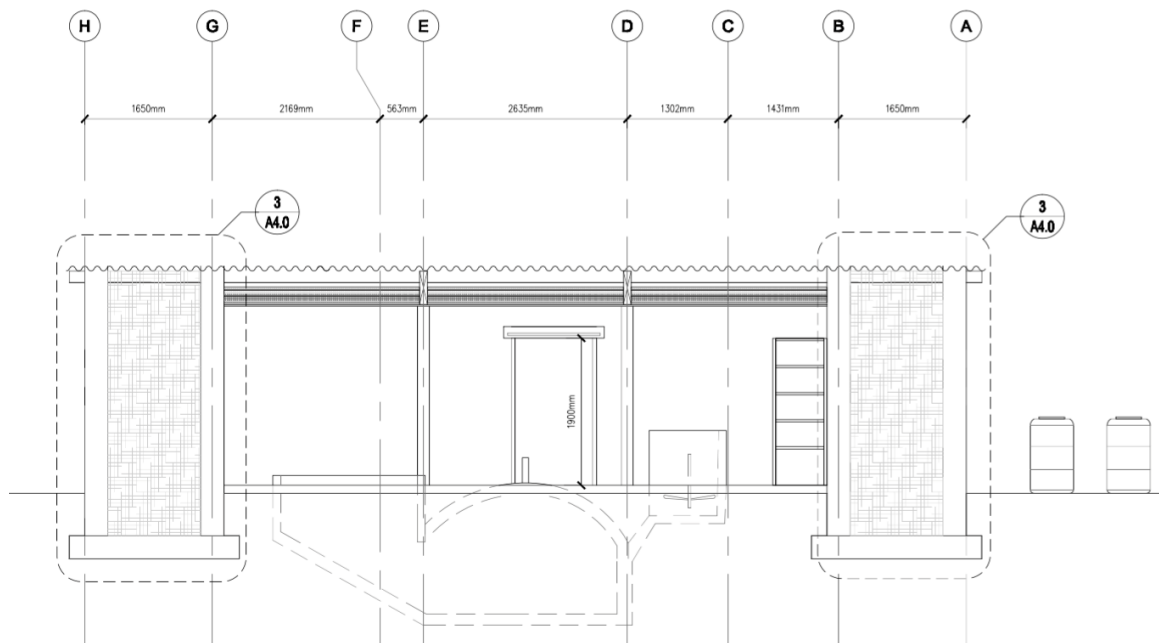


Figure 11



Figure 12

Inside the building there will be access to the biogas digester inlet and outlet. The BSP $\sim 6 \text{ yd}^3$ (6 m^3) digester will be insulated to R-50 USCS (R-8.81 SI) to reduce heat loss to the ground and air inside the building. The base of the digester will be insulated with polystyrene foam underneath. The walls & dome will be insulated with polyethylene foam, continuously wrapped around the wall. There will also be a vapor barrier outside the insulation to prevent water from entering and decreasing the insulation's effectiveness. All of these materials are available in Kathmandu, strong enough to survive transport to Gorak Shep and commonly used in the Khumbu valley for insulation.

B)

The rain water for mixing slurry will be stored in five $\sim 792 \text{ gal}$ (3 m^3) tanks inside the building. That is $\sim 3,963 \text{ gal}$ (15 m^3) of water will be stored in total. Storing the water inside the building will prevent freezing in the harsh winter months. The waste for making slurry will be stored in an accompanying shelter with a hand-powered augur to remove solids. The waste storage is explained as part of section C below.

The rain water collected on the roof will flow from a gutter into the building through a single pipe. Inside the building there will be a filter installed before the water tanks to remove grit and debris. At the end of the monsoon and before weather brings snow instead of rain, the gutter will be closed off with a rubber stopper. The rubber stopper will act as a thermal break, stopping heat loss from the piping inside the building to the outside of the building.

The building's window will have an insulated cover, opened in the day to allow solar heating and closed overnight to insulate the building. The solar energy gained during the day time will increase the stored water's total temperature and allow it to act as a tromb wall, radiating heat into the room when the windows are closed. However, the contribution of passive solar water heating has been neglected from heating calculations, but neglecting this contribution adds another layer of safety to the design.

C)

The human waste that will be mixed into slurry will be stored in three ~1,320gal (5m³) tanks set into the hillside at the back of the shelter. These cool, in-ground tanks will reduce odor when waste is put into storage and while it is held there. This storage will also allow easy retrieval of the waste when making slurry; letting operators measure out waste for one batch of slurry with the screw augur. This solution has been presented instead of storing dozens of blue barrels and scraping out the needed waste when the barrel is almost empty.

The function of this storage is to hold the waste at a temperature low enough to prevent the biological action of organisms in the waste. Such aerobic biological activity will consume the volatile fatty acids (VFA) available in the waste. This will cause unpleasant odors and rob the digester of the carbon that could otherwise become the methane in the biogas. This waste storage will also prevent freezing of the waste. However, if some of the stored waste does freeze, waste can be removed from storage with a shovel and be put in the "thaw shed", see Figure 9 above. This thaw shed will allow easy solar heating of waste held in buckets, the day before it is mixed into slurry. To avoid waste freezing, the storage will also be insulated with polyethylene foam. By making the waste storage out of prefabricated items available in Nepal and transported to the site, the project will avoid the risks of leaky storage if masonry were used instead. It should be mentioned here again that this is a preliminary design, subject to later refinement as the project moves toward implementation.

Element 2

Our analysis of the digester's heat loss, in the conditions for the winter design case (assuming 86°F (30°C) inside the digester and 23°F (-5°C) in the soil) showed that the digester would lose 351.54 BTU/hr (103 W) a day. To reduce risk with this critical case, the calculations for sizing Element 4 assumed about twice this amount of heat to be lost by the digester. That is 682.60 BTU/hr (200 W) daily, thus providing a safety factor of 2 in the winter design case. This can be accomplished with a 200 W Venus Coil Type immersion heating-element. This heating-element will be placed directly into the digesters middle, via the digester's outlet. The heating-element is available in Kathmandu and strong and small enough to be easily transported to the site.

Our analysis of the digester's heat loss in the summer design case (assuming 86°F (30°C) inside the digester and 32°F (0°C) in the soil) showed the digester would lose 262.80 BTU/hr (77 W) a day. Since this design case was chosen for reasons of available solar energy and not extremely low temperatures, this heat loss was not doubled. But to remain conservative in all design work, the heat loss in the summer design case was rounded up to 100 W or 341.30 BTU/hr when sizing Element 4 in the summer design case.

Because the heating system, here named Element 2, must be able to function in both the winter and summer design cases, the 200 W Venus Coil Type immersion heating-element was chosen (instead of a 100 W unit).

Element 3

During the coldest days of the digester's operation, the 17.6 gal (66.67 L) of slurry that must be fed to the digester daily, may need to be heated from 32°F to 86°F (0°C to 30°C). For design purposes, we have assumed that this will require an additional 511.95 BTU/hr (150 W) heat source for each day's batch of slurry. It is a requirement of this design, that the additional energy demand must be available daily.

To arrive at the value of 511.95 BTU/hr (150 W), the energy to heat up each day's batch of slurry was calculated with the specific heat equation:

$$q = (c_p * m * \Delta T) / t$$

Where q is mean heat transfer rate (kW), c_p is specific heat capacity of the substance being heated (KJ/Kg°C), m is the mass of the substance, ΔT is the difference in the substance's final and initial temperatures (°C), and t is the heat up time (s).

To be conservative, the specific heat capacity of human waste was assumed for the slurry. This is a difficult value to define, but the value of 5 KJ/Kg°C listed for wet feces in US patent: US20130341175, was used in the calculation. (<http://www.google.com/patents/US20130341175>)

$$q = (5(KJ/Kg^{\circ}C) * 66.67(Kg) * (30^{\circ}C - 0^{\circ}C)) / (24hr * (3600s/hr))$$

$$q = 0.1157 (KW) \text{ or } 115.7 W$$

To be conservative once again, it was decided to set the design requirement to 150W (511.95 BTU/hr). This was done in case some of the slurry was not just at 32°F (0°C), but beginning to freeze. To achieve this heating a 150 W Venus Coil Type immersion heating-element, similar to that described in **Element 2**, would be used.

Element 4

Similar to the work shown in the **Digester Sizing and Logistics** section, the writing below uses SI units, as they are the industry standard for solar panels and US customary system units would not be helpful or make sense.

There are two difficult times to operate this system; the summer monsoon season, when clouds decrease the amount of solar energy collected with PV panels, and the winter when more heat is lost by the digester into the colder ground. By evaluating NASA weather data for Gorak Shep, we have found that the summer monsoon season is the most difficult time to harvest the required

energy for the digester. A design of solar panels and batteries was done for both seasonal extremes, and even though the energy required for Elements 2 & 3 is smaller during the monsoon, the low amount of solar energy available in July (due to cloud cover) requires a larger PV panel and battery array. The heating demands of January are larger, but more easily supplied for several consecutive days due to the fewer cloudy days. Thus the design described in **A & B** below will be able to function in both the monsoon and winter extremes.

A)

The critical value in sizing the PV array is the “Peak Sun Hours” (PSH). This is defined as $1000\text{W}/\text{m}^2/\text{h}$. It is a useful unit of measurement since the nominal power rating of solar modules is defined at $1000\text{W}/\text{m}^2$, so given a PSH and a PV array size, daily energy production can be estimated. The NASA weather data was compiled and compared to the design values used by local solar engineers and they were close to each other. For example, the NASA data showed $\text{PSH}=3.59$ for July, while the Nepalese solar engineer, Jeevan Baidya from Gham Power in Kathmandu, recommended a value of 3.5. This was the heuristic number used by Gham Power to expand the PV array of the Italian research station EVK2, which has been in successful operation at Luboche since 2012.

The NASA weather data for Gorak Shep was reviewed and it was determined that the critical design months were either January or July, based on average daily solar radiation for those months. January has shorter days and hence has a low total amount of radiation, while July had longer days but long periods of overcast weather. It was also determined that seven days of operation/heating would be required to maintain suitable digester temperature. The PV array and battery bank design hence uses seven days of operation as part of the design criteria.

The first step was to size the PV array. Since the load is 350W in January and 250W in July, and keeping $\text{PSH}=3.5$, July required a larger PV array in order to charge the battery bank, using the daily average PSH for those months. This resulted in a PV array equal to 3.2kW.

Final PV array sizes also had to take into account the locally available module wattage and voltage, as this would affect the number of modules installed in series. Assuming the use of a Maximum Power Point Tracker controller (MPPT controller), two modules in series offer the ideal operating voltage. That is, voltage low enough to ensure higher conversion efficiency and cooler operating temperature of the controller, but also voltage high enough to ensure operation of the charge controller during warmer temperatures, when PV module voltage decreases. The project team is already in contact with Gham Power, a Kathmandu based company that installed a 10.39 kW solar panel array for the Italian research station EVK2 in Luboche in 2011. The successful operation of these solar panels since 2012, so near to Gorak Shep, makes them a perfect choice for the digester’s system. These panels, available from Gham Power, are 200W each. Since these locally available modules are rated at 200W at Standard Test Conditions (STC) and two are used in series for each circuit or string, the PV array was to be sized in 400W units. With this in mind, the limiting design case of July required a PV array size of 3.2kW, to supply the necessary energy for Elements 2 & 3. The PV array (8 strings*400W per string) of 16 solar panels, can be managed by a single charge controller.

To determine the minimum PV array size (W), the average daily load (Wh) was divided by the average daily PSH (h). A conversion efficiency factor of 0.75 was also incorporated, to account for module derating due to temperature, age degradation, soiling, wiring losses, panel mis-match, and other factors. A typical industry-wide accepted default value for this overall conversion is 0.77, used for example by PVwatts, the NREL developed PV performance simulator. So the use of 0.75 was a slightly conservative assumption.

Since it was determined the digester would lose enough heat to fall into less gas productive temperatures (below 10°C) after more than seven days, the next step was to determine the amount of PV production during the worst (lowest producing) 7 day period of the year. The NASA data provides this, as data points called “Minimum Available Insolation Over a Consecutive Day Period”, expressed as a percentage. These values were used to determine how much the electrical load would be offset by PV production during the seven day design period. The amount of insolation available during that period was also factored into the PV array sizing. That is, the typical “days of autonomy” approach toward battery sizing was not used, as this neglects the contribution of the available solar resource, even if it is small.

For January, it was found that the lowest average insolation during a seven day period was 3.17 peak sun hours (PSH). For July, it was 2.03 PSH. As mentioned above, July’s limiting case of minimal Peak Sun Hours controlled the sizing of the PV array. In summary, the PV array proposed is a 3.2kW array made of 8 strings*400W per string, for 16 solar panels total.

B)

It was determined that the 48V battery bank to supply the necessary energy for Elements 2 & 3 must have a minimum 268 Amp-hours capacity at the C/100 rate. To achieve this, battery bank of 24 batteries per string will be used. The batteries will be Exide two volt cells, which are also available through Gham Power. These gel batteries are less efficient than other ion solution style batteries available. However, gel batteries have been chosen for this project because of their robust nature, which does not require the maintenance needed with ion solution batteries. With this design the batteries will only cycle to a max discharge of 80%, if there were to be seven days of battery discharge. This practice should ensure a long lifespan of at least 9 years for these particular batteries.

The battery available to us for this project is the Exide LMXT. Since some specifications for this battery were not available, the missing specifications were taken from a battery that uses the same chemistry. The value for battery capacity rating as a function of temperature was taken from the SBS 2 TGI batteries, which is also a tubular gel battery.

Since the load was to be powered for seven days, the daily load for both design months was multiplied by seven. The energy input during this seven day period was also determined by taking the Average Worst Peak Sun Hours (AWPSH) and multiplying it by the PV array size determined for the design month. This amount was subtracted from the seven day load. This net load was then divided by the maximum allowed depth of discharge (80%), to ensure that no

damage to the battery bank would be caused by an excessively deep discharge. This load, expressed in units of amp-hours (Ah), was then divided by 0.88 to correct for a low temperature of 50°F (10°C). While there was no temperature data on the Exide LMXT, the SBS 2 TGI batteries had this information, so as an approximation, it's value of 0.88 was used. This set of calculations was performed for both January and July. The month that resulted in the larger battery bank was July, which will require 48 two volt batteries.

The average daily depth of discharge for the batteries is only about 10%, which according to the datasheet for the battery, will result in a lifespan of over twenty years. Based on professional experiences, our PV Engineer expects these type of sealed batteries to see a maximum lifespan of about ten years.

There is one final issue to be considered with the battery bank. In the upper Khumbu Valley of Nepal, batteries can freeze and break. This problem is usually prevented with heat from gas-powered generators. For this project the batteries will be prevented from freezing by insulating the battery bank storage. The insulated storage will also be inside the shelter building, designed to maintain temperatures above freezing. This double protection from cold weather will be more than enough to keep the battery bank above freezing.

Next Steps for the Project

The intention of this document has been to describe the problem of human waste pollution at Gorak Shep and the feasibility of solving it with a Nepalese biogas digester design adapted to solve the issue of heat loss. There are many other aspects of this project, critical to its long-term sustainability, that are not covered in this document as they are not technical in nature. But it should be noted that in May 2016 members of the MEBP met with the leadership of SPCC and the local Buffer Zone Committee in Namche Bazar. The meeting ended with a three part memorandum securing long-term local ownership and operation, with remote support from MEBP team members in Nepal and the U.S. (See **Appendix E**).

It should also be mentioned that before implementation, the final design will be built and the digester and storage tanks filled with water, to allow a trial run of the system. In this trial run the minimum temperatures found in the system during the winter will be documented to ensure biologic activity can be kept warm enough and to double check the size of the PV array and battery bank. This will allow the design and implementation team to determine any deficiencies or excesses in the design and correct them before using the system to treat waste.

To finalize our design and move towards construction the MEBP will work to accomplish the following goals:

- Use soil infiltration and soil data taken during a May 2016 site survey to Gorak Shep to design the drain field. This data will be used to follow septic tank drain field design concepts to define perforated pipe sizing for disposing of digested slurry.
- Meet with Nepalese Contractors from the Khumbu valley to define budgetary prices for building the above biogas system at Gorak Shep.

- Begin fundraising efforts using budgetary pricing from Nepalese companies.

Through collaboration with Nepalese experts and local community members, the Mount Everest Biogas Project seeks to refine its design and successfully implement and sustainably operate biogas digestion at Gorak Shep.